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Applicability of long-range seismic noise correlation for CO_2 geological storage monitoring

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Abstract

As correlation of broadband seismic noise begins to be used for long-term monitoring of geological objects, we assess the theoretical feasibility to monitor CO_2 geological storage with this method. We use the Ketzin pilot project speed profile in order to compute the theoretical speed perturbation of Rayleigh waves, and we compare them to natural variations recorded on the field using a broadband network.
Our results show that, if we consider a theoretical demonstrator-scale injection at the Ketzin site, the perturbation induced by the CO_2 bubble is greater than recorded natural variations. We show that the method is sensible to CO_2 bubble cross-sections: a 3D tomography is therefore possible with a carefully placed network. For a CO2 geological storage geology similar to Ketzin, the minimum cross-section that can be detected is 100 000 m², 500 meters wide if the whole 200m reservoir level is filled.

Keywords: monitoring, seismic noise, CCS

1. Introduction

For about ten years, studies have shown that it is possible to determine the elastic response of earth from a random field of seismic waves [1]. Lobkis and Weaver [2] laid the foundations of this theory; they showed that, after a sufficiently long time, the cross-correlation between one pair of receivers situated in a diffuse wave field amounts to the Green's function between these receivers (only the amplitude is different). In other words, the Green's function, i.e. the impulse response of a medium, can be extracted from the computation of the cross-correlation between two receivers. This theory has been validated in the

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field of seismology since then by many works, using the seismic coda as first [3] and more recently the ambient seismic noise [4] [5] [6]. Seismic noise correlation might be used either for passive tomography [6] or for velocity changes monitoring [7].

This method represents an interesting alternative for the active monitoring methods currently used: it is cheaper, and the ambient noise correlation allows a continuous monitoring; therefore, the possibility of using it in the field of CO_2 geological storage has been recently proposed [8].

However, correlation of seismic noise highlights mostly Rayleigh and Love waves, and therefore the perturbations induced by the injection on such waves need to be evaluated in order to assess the sensitivity and the limits of this method for CO_2 geological storage.

In this paper, we study the theoretical applicability of this method to detect any changes due to CO_2 geological storage; for this purpose, we first estimate the speed change induced by CO_2 presence for a 1D realistic model of CO_2 storage ; according to the outcomes of this assessment, we then discuss the conditions in which the method would be applicable. For the purpose of the study, we will consider a theoretical demonstrator-scale injection at a site similar to the Ketzin injection site, Germany. This allows us to take advantage of the wealth of information available on this site, thanks to the multiple experiments and models done in the European projects CO2SINK, CO2ReMoVe and CO2CARE, although this site is a injection pilot thus limited in size by European legislation on CO_2 storage pilots ; the injection modeled is however not the one planned for the actual site.

Nomenclature

v_l , ρ_l	S-wave speed and density of brine-filled reservoir rock
v_g , ρ_g	S-wave speed and density of CO_2-filled reservoir rock
t_{CO2}	time spent by the Rayleigh wave in the CO_2 bubble
d_{CO2}	length of the CO_2 bubble
h_{CO2}	thickness of the CO_2 bubble
a_{CO2}	section of the CO_2 bubble, defined by the length times the thickness
v_R	Rayleigh wave speed

2. Can we detect CO_2 injection induced perturbations using Rayleigh waves from noise correlation?

2.1. Effect of CO_2 injection induced perturbations on Rayleigh wave speed

The effect of fluid saturation influence on body waves velocity is often studied using Gassmann theory [9]. The bulk-modulus is modified with the saturation, meaning that P-waves are dependent on fluids. The S-waves are however only sensitive to fluid density modifications, the shear modulus being generally considered as constant. However, such analysis does not take into account the rock properties variations due to pore pressure changes [10]. Some studies [11] show that S-waves and P-waves are both modified during CO_2 flooding under CO_2 storage conditions. For instance, in the carbonate reservoir in West Texas, USA the average velocity variations have been reported to be of -6 % for P-waves and -5 % for S-waves.

Rayleigh waves are surface waves generated by the interaction of P and S waves with the free ground surface and the seismological layers. As a combination of S and P-waves, the Rayleigh waves speed modification is, thus, not straightforward. Because of their nature, Rayleigh waves are dispersive, and their dispersion as well as their penetration depend on the body-wave velocity profile. However, potential targets for CO_2 geological storage share the same features: a subsoil structure, a strong caprock above a soft reservoir layer; it is therefore believed that, although numbers may vary, the Rayleigh wave speed dispersion main features will remain the same.

In this work, we propose to assess the effect of CO_2 presence injection induced perturbations on Rayleigh wave speed using the velocity profile from the pilot site at Ketzin, Germany. This profile is showed in Juhlin et al [12] ; the reservoir is at shallow depths and shadowed by a very strong mudstone and anhydrite caprock. We assume that, for an hypothetical demonstrator-scaled injection, pressure effects will appear with saturation effects, thus affecting the S-wave speed. Since few data for body-waves changes under CCS conditions have been provided, we use the average velocity modification provided by Wang et al [11] : 6% decrease for P-waves and 5% decrease for S-waves.

We then compute Rayleigh wave speeds for several profiles:

- The initial profile, without CO_2;
- We then divide the reservoir layer into two parts, with the upper part affected by the speed perturbation induced by CO_2 presence. We compute Rayleigh speeds for different upper layer thicknesses, from 10m to 200m (the whole reservoir thickness).

Results are shown on Figure 1 : the maximal group speed perturbation is obtained for the 0.4-1 Hz frequency range, and can attain 3% when the reservoir is filled with CO_2.

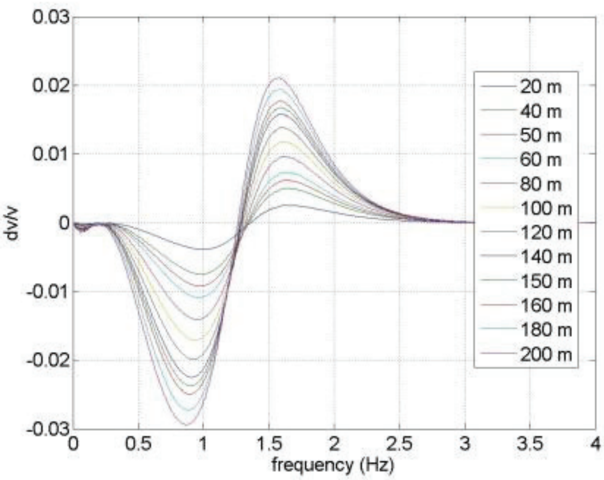
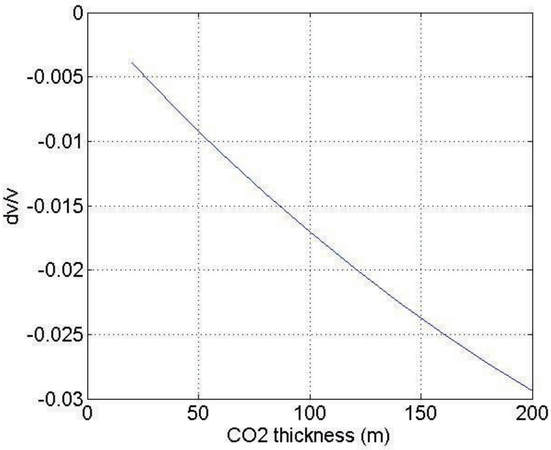


Figure 1: speed perturbation dv/v dispersion for different CO2 layer thicknesses.

If we plot the maximal speed perturbation against the CO_2 layer thickness, we see that we have an almost linear relationship between the two, as shown in Figure 2. This linear relationship is due to the fact that, at this frequency, the Rayleigh wave profile is sensible to the whole reservoir level; therefore, as we



increase the thickness of the CO_2 layer, we increase in the same proportion the speed perturbation.

The initial Rayleigh dispersion profile, which will be needed for dv/v calculations, is shown below :

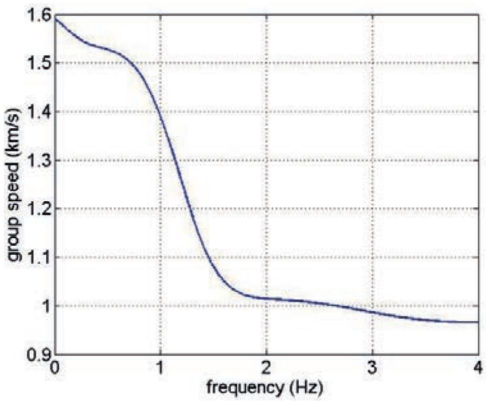


Figure 3 : group dispersion for the Rayleigh waves in the case of Ketzin velocity profile

2.2. Theoretical thresholds for perturbations detectability

Once we get the theoretical perturbation on Rayleigh wave speeds, we can assess the perturbed zone minimal dimensions that can be estimated by Rayleigh speed perturbation methods, i.e. the minimal detectable footprint of the CO_2 geological storage. Since seismic methods measure delays, we estimate the time delay caused by the injection induced perturbations compared to the initial situation:

$$\delta t = -\frac{\delta v}{v} \times t = -\frac{\delta v}{v} \times \frac{d_{CO2}}{v_R},$$

where δt is the time delay associated to the arrival time t, $\frac{\delta v}{v}$ is the relative velocity change due to the perturbations, d_{pert} is the perturbation distance and v_R is Rayleigh waves velocity.

Knowing from Figure 2 that $dv \,/\, v$ is proportional to the CO_2 layer thickness (denoted h_{CO2}), we can therefore write:

$$\delta t = -\frac{\delta v}{v} \times \frac{d_{CO2}}{v_R} = -\alpha \times h_{CO2} \times \frac{d_{CO2}}{v_R},$$

which means that the time delay is proportional to the CO_2 cross-section $a_{CO2} = d_{CO2} \times h_{CO2}$.

If we consider a classical broadband sensor sampling time of 10 ms, and a Rayleigh wave speed at 0.85 Hz of 1.45 km/s (computed during the definition of the reference speed profile), we get a minimum cross-section of 100000 m²; if the CO_2 occupies the whole reservoir level, the minimal length of the CO_2 bubble is therefore 500 m.

It is worth mentioning that the minimal length estimated does not depend on the way we measure Rayleigh wave speed, by SASW methods, direct measurements of Rayleigh waves obtained by noise correlation or coda stretching of these Rayleigh waves. Noise correlation offers a permanent cheap monitoring, while SASW is more precise at the expense of time-lapse measurements and strong (and thus expensive) sources.

2.3. Comparison between pre-injection speed variations and modeling using Ketzin measurements of background noise.

The previous estimation holds only for theoretical conditions, when the only perturbation comes from the CO_2 injection. In real conditions, however, several natural variations can occur: seasonal variations, aquifer changes, etc. Speed variations generated by these natural factors have therefore to be lower than the speed perturbation caused by the injection operations.

During 2009, a broadband network was installed on the Ketzin pilot site in order to test correlation methods. Since the injection started in 2009, the network was able to record the ambient seismological noise when the injection perturbation was too small to have a sizeable influence, and we can therefore estimate the natural variability for this site.

Crosscorrelations were computed following Bensen et al [13], using 15 day stacks; they were then compared using stretching techniques [14]. Results are shown in : dv/v variations are cyclic and do not go over 2% .This result shows that natural variations *in this case* do not hamper the monitoring of the CO_2 perturbation zone, provided that enough averaging time is used to smooth out the daily variations. Noise correlation is therefore a viable long-term monitoring tool for Ketzin CO_2 storage in the case of high stored volumes.

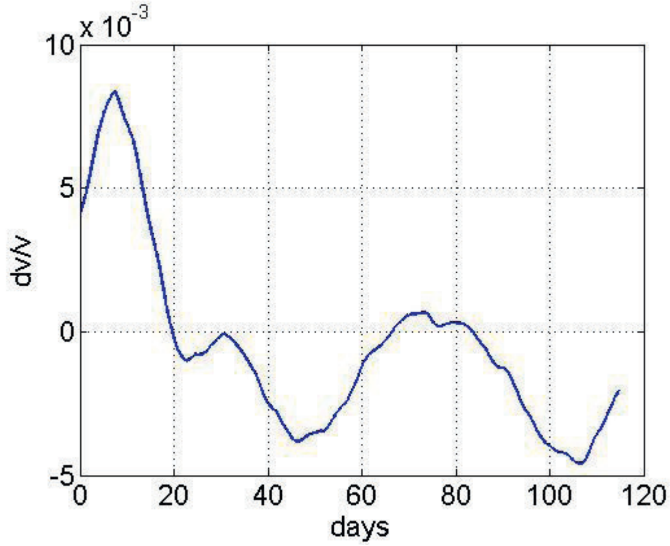


Figure 4 : observed dv/v at Ketzin from end of June 2009. The reference function used was the mean of all Green functions during this period.

3. Conclusion

Our study shows that monitoring the changes in Green functions retrieved by correlation of seismic ambient noise can bring a new tool to follow medium-sized CO_2 geological storages: in the theoretical case we studied, a 100 000 square meter can be tracked through this method. With a network surrounding the CO_2 bubble, it is possible to monitor the total volume through multiple correlation lines and 3D tomography. Thickness of the CO_2 bubble may be constrained with 3D tomography; thickness effect could also be seen in the frequency changes for speed perturbations, although this study didn't cover this point.

There are, however, several points to keep in mind The first point is that, like other geophysical methods (active seismic, electromagnetic, gravimetric), a baseline is mandatory to establish the reference function and measure the natural fluctuations. The advantage of noise correlation is that, once the baseline is established, the monitoring can be done continuously at a lower price than active time-lapse methodologies.

The other caveat in using correlation of seismic noise is that each site is unique for three reasons :

- The velocity profile will change from one site to another, leading to different critical frequencies to monitor and thus possible changes in hardware (for example, for a deeper storage site, lower frequencies may lead to use broader band seismometers)
- Noise source distribution for each site may lead to different noise conditions which have to be analysed
- Velocity changes are sensible to pression as well as CO_2 presence; each site will see different pression buildups, and thus the sensitivity of this method will change for each case.

It is therefore of utmost importance to study each site beforehand, by getting the baseline and a velocity profile properly and coupling velocity change studies with fluid transport studies in order to assess the pressure effect

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